A Numerical Model Of Puget Sound Circulation

Mitsuhiro Kawase
School of Oceanography, University of Washington

Introduction

We report here early results from a numerical model of marine circulation in Puget Sound, which is to form an element in the Puget Sound Regional Synthesis Model (PRISM) project at the University of Washington. PRISM is a project supported by the University of Washington University Initiative Fund (UIF), and its aim is to develop and consolidate university-wide expertise in the Puget Sound region's natural and human environment. The circulation model is fully three-dimensional, and is designed for reproducing the Sound's circulation over tidal to interannual time scales. We intend to develop a predictive capability for Puget Sound circulation pertinent to such issues as water quality, pollutant dispersal, and harmful algal bloom development. It is our intention to make this model eventually a component of a regional earth systems model in which it would interface with meteorological and hydrological models and would incorporate models of biological productivity and transport of contaminants.

The Model

The circulation model is based on the Princeton Ocean Model (POM, Blumberg and Mellor, 1987), which has been used extensively in coastal and estuarine studies. The model equations are those of the standard primitive equation (hydrostatic) dynamics. Given initial and boundary conditions, the model predicts in time sea-surface elevation, three components of circulation velocity, temperature and salinity as well as turbulent kinetic energy and turbulent mixing length. The latter two are used in parameterizing vertical eddy mixing in terms of turbulence closure scheme of Mellor and Yamada (1974). Surface elevation and depth-averaged velocities are integrated separately from internal quantities in a split-explicit formulation.

The model domain (Figure 1) covers the entire Puget Sound from Admiralty Inlet inwards, as well as a part of the Strait of Juan de Fuca, at a 600-m resolution in the east-west direction and 900-m in the north-south direction. Bathymetric data were supplied at 300-m resolution by Dr. Miles Logsdon of the School of Oceanography, University of Washington. The data were then subsampled at model grid points. This resulted in inadequate resolution at several locations. Bathymetry was further manipulated at these spots as follows:

- Branch channels and inlets that could be represented by only one grid point across were blocked, and isolated bodies of water thus formed were filled, except:
- Hood Canal at Sisters Point was enlarged.
- Islands with only one grid point and fully surrounded by water were eliminated.

In addition, cut-off was made at ten meters depth, eliminating much of shallow tidal flats; the current version of the model does not handle wetting/drying during a tidal cycle. Ocean depth in the Strait of Juan de Fuca was set to 100 m. The region outside of Admiralty Inlet is intended as a holding area in this model and is not actively modeled.

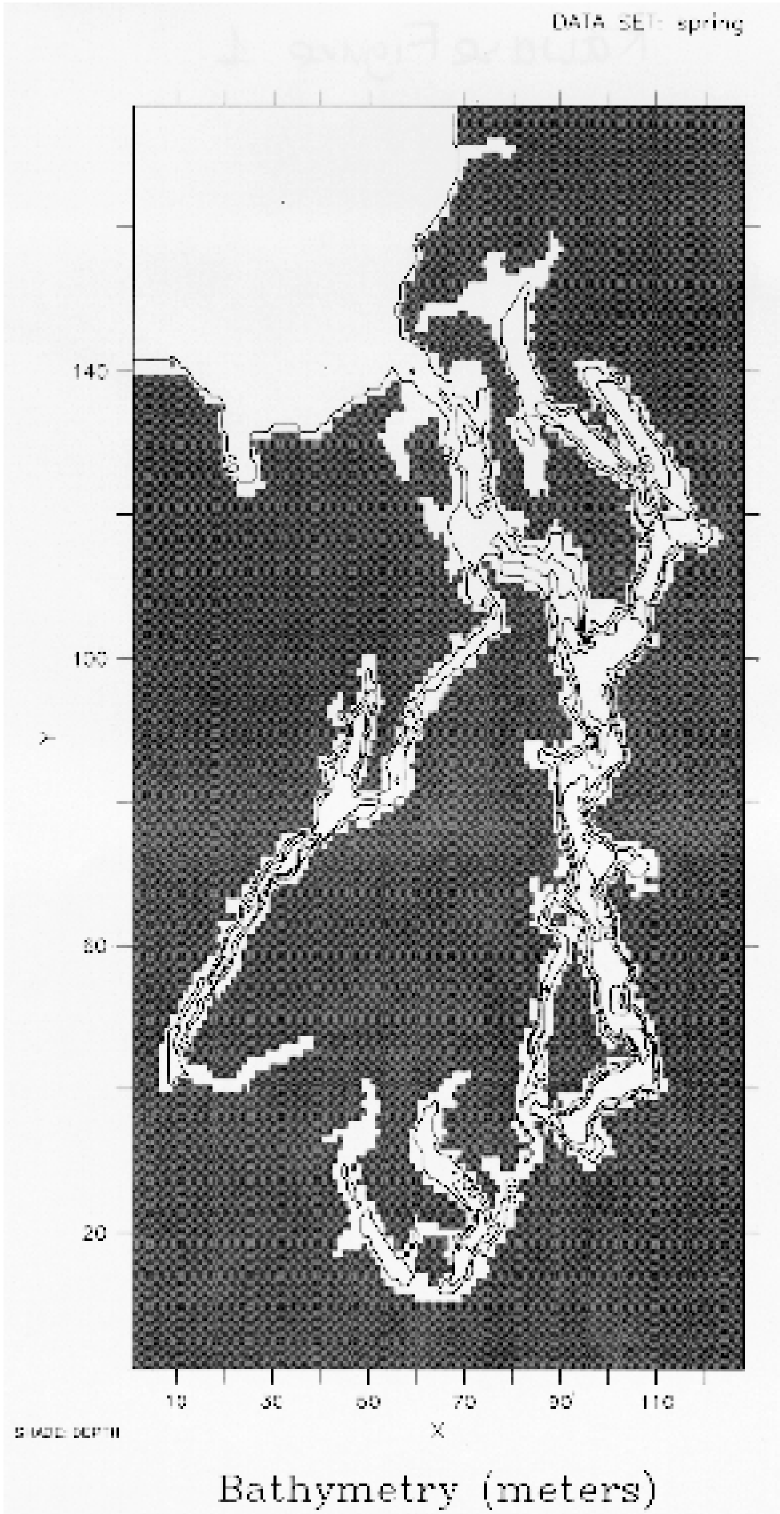

Figure 1. Model Domain and Bathymetry.

The model responds to wind stress, heat, and fresh water fluxes applied at the sea surface as surface boundary conditions. Boundary conditions at the bottom are no mass, heat and salt flux, and bottom stress in terms of quadratic drag. River input is specified as mass and fresh water sources at grid points nearest to the geographical locations of river mouths. The model has an open boundary in the Strait of Juan de Fuca, where tidal forcing is incorporated as boundary conditions using Flather's (1976) scheme. Seven tidal constituents (M2, K1, S2, N2, O1, P1, M4) were used in forcing, in emulation of an earlier channel model of Puget Sound tides by Lavelle et al. (1988). In addition, a radiation boundary condition was applied to external and internal modes of velocity, while temperature and salinity were either advected out or set to a prescribed value when advected in.

Results

In this proceeding, highlights from the model's barotropic tidal circulation will be reported. This is by no means an exhaustive verification even within this restricted scope; the richness and complexity of the model's response, as well as the wealth of data available for the Sound, opens many further avenues of comparison.

Sea Level

Time series of sea level were generated at 43 grid points that correspond to locations of a subset of tidal stations reported by Lavelle et al. (1988). They were regressed against the seven forcing frequencies and resultant amplitude and relative phase of each tidal constituent were compared with observed amplitude and relative phase. (By relative phase we mean phase value relative to an arbitrary base line; in this case the average of all phase values for a given component.) Figure 2 plots modeled amplitude and relative phase for the semi-diurnal M2 component, which is the most dominant, against the observed for all stations. Overall agreement is excellent for amplitude; the modeled phase range is also in excellent agreement with the observations, but there is a tendency for the modeled phase to cluster around several values, indicating that each sub-basin of the model tends to oscillate more or less in phase within, while in reality the M2 tide shows more propagating tendency. This is indicative of insufficient dissipation of tidal energy in the model, which tends to set up standing oscillations within each basin. Lavelle et al. (1988), in the modeling part of their study, also noted a need for stronger-than-usual dissipation in modeling Puget Sound tides correctly.

Similar agreements were found for other components of the tidal variation of sea level. Figure 3 shows a similar comparison for the K1 component; observations show that, generally speaking, diurnal components have narrower phase lags and more uniform amplitude distributions than semi-diurnal components; this was reproduced well in the model response. The tendency for the model phase value to cluster was more pronounced for diurnal frequencies.

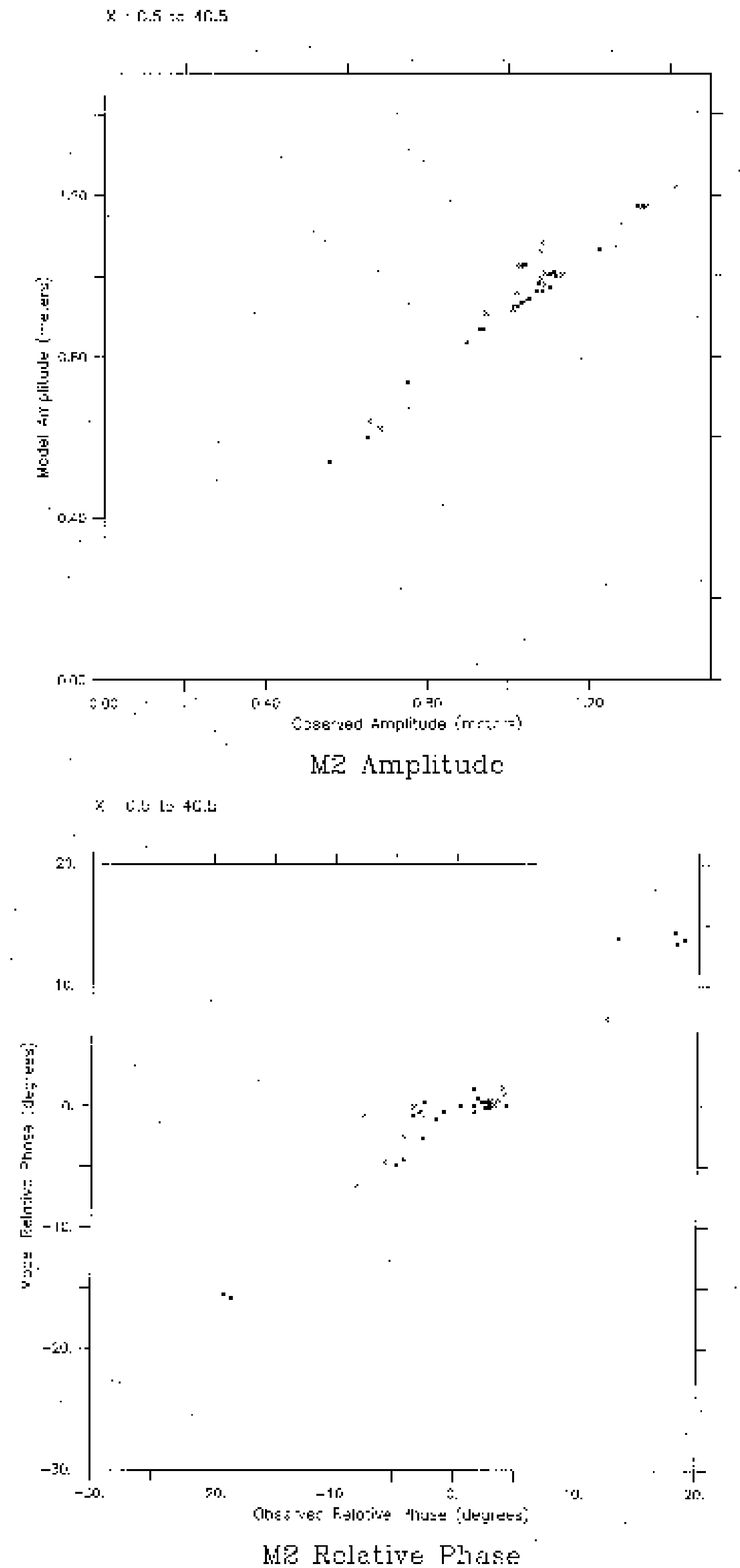

Figure 2. Comparison of observed and modeled M2 tide. Observed (horizontal axis) versus modeled (vertical axis) amplitude (left) and relative phase (right).

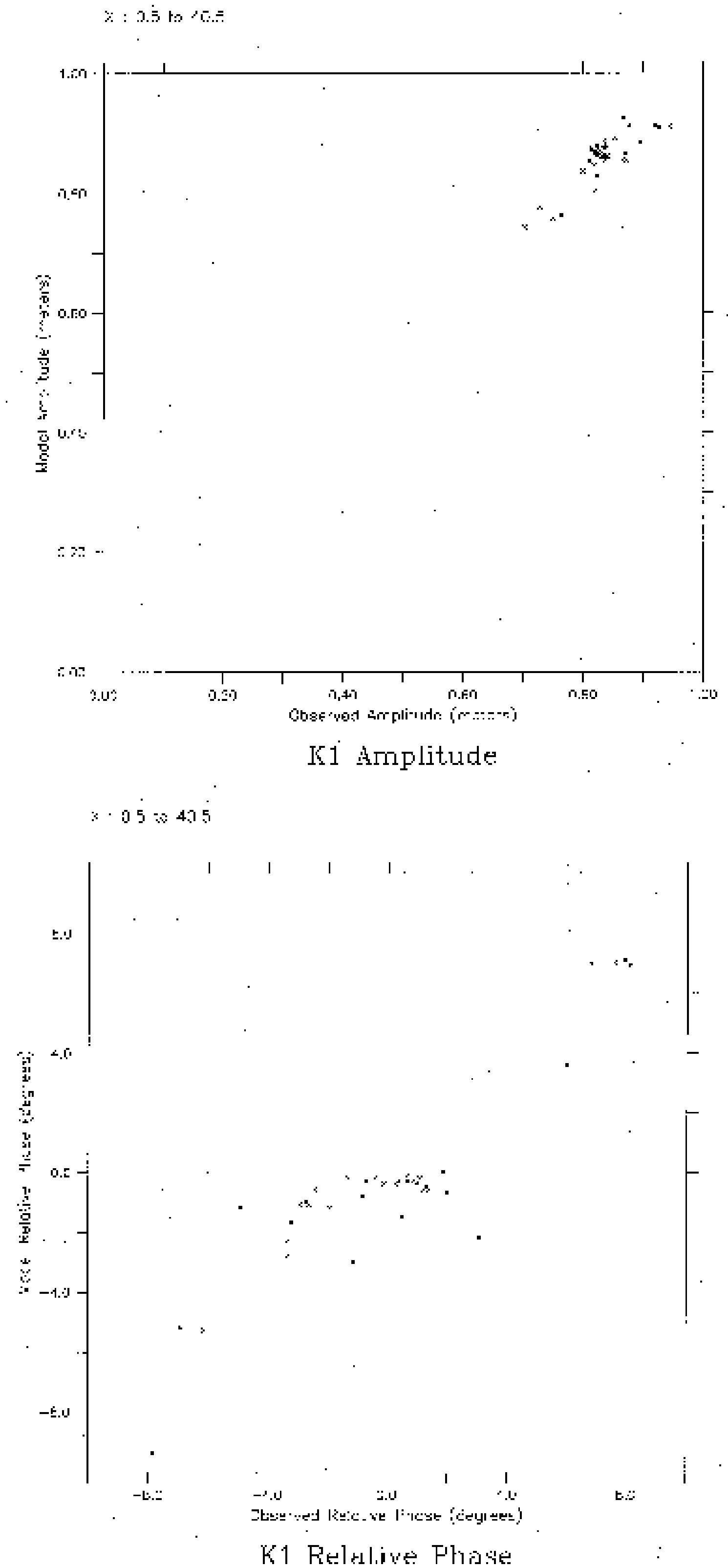

Figure 3. Comparison of observed and modeled K1 tide. As in Figure 2.

Currents

Strong tidal currents occur through Admiralty Inlet and Tacoma Narrows. In addition, strong currents are observed in Hood Canal north of Seabeck Bay. Tidal currents through Admiralty Inlet reach speeds in excess of 2.5 m/sec, while in Tacoma Narrows speeds exceed 2 m/sec and in Hood Canal speeds reach 1m/sec. The maximum current in Admiralty Inlet in the model occurs between Admiralty Head and Point Wilson–Marrowstone Point (Figure 4).

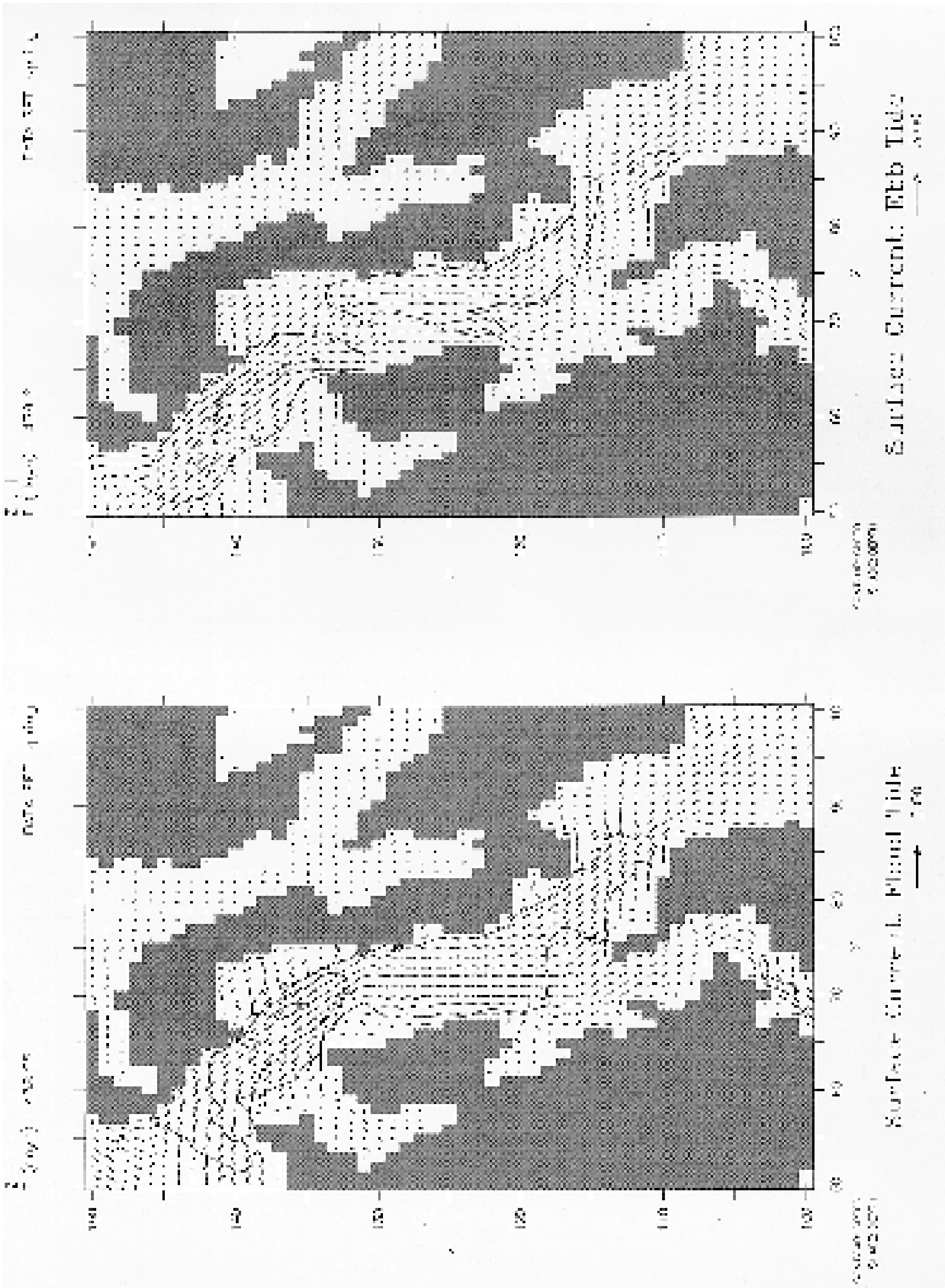

Figure 4. Surface current in Admiralty Inlet. Current direction (vector) and speed (contour). Left: maximum flood tide. Right: maximum ebb tide.

Velocity components were regressed against M2 and K1 frequencies at several points in the model where current meter records exist. Figure 5 shows current ellipses at the surface along an east-west section at Bush Point in the model, which corresponds to a MESA current meter section reported by Cannon et al. (1979) and analyzed by Mofjeld and Larsen (1984). Both M2 and K1 components have realistic semi-major axis amplitudes (1 m/sec for M2 and 45 cm/sec for K1). Moreover, the model reproduces slight intensification of M2 current towards Whidbey Island and maximum of K1 current at the center of the channel, both observed features in the current meter records.

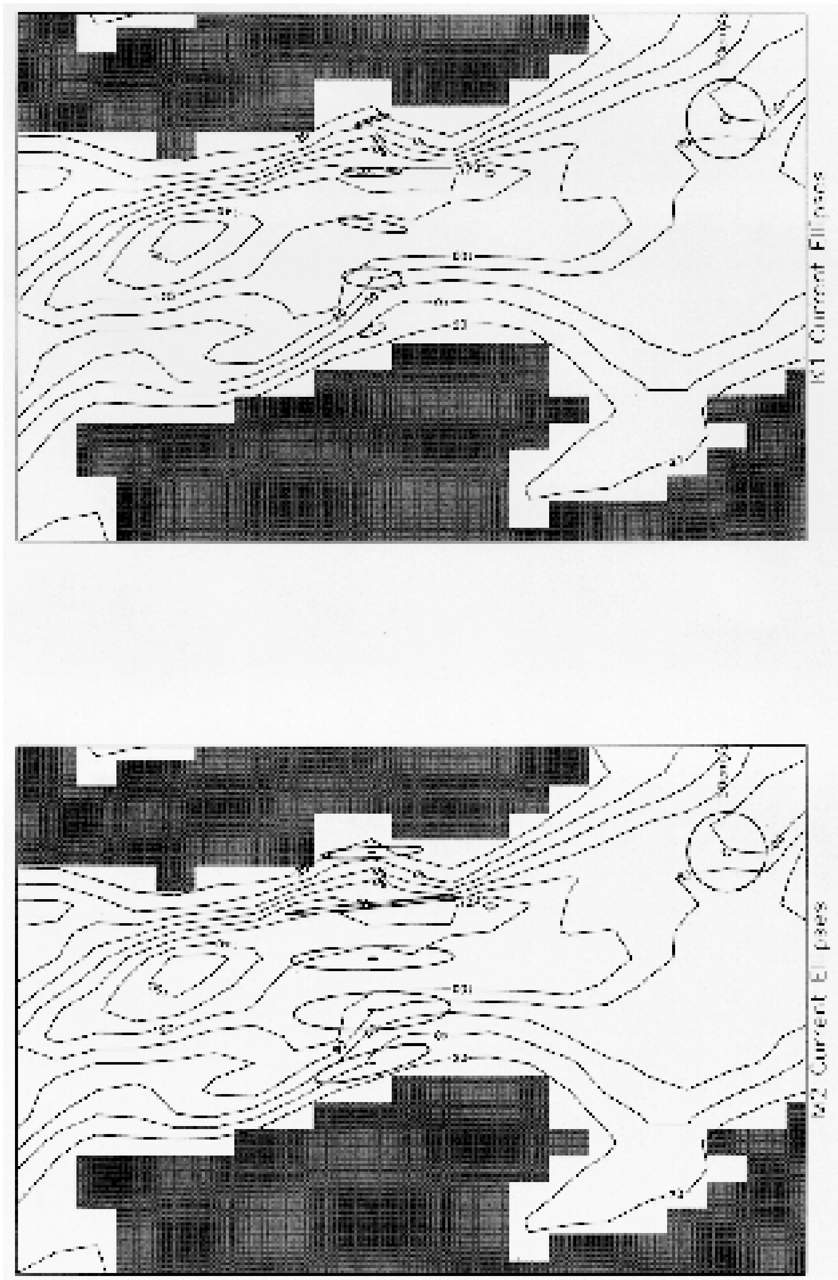

Figure 5. Tidal ellipses in Admiralty Inlet, roughly corresponding to the location of current meter section by Cannon et al. (1979). Left: M2 component. Right: K1 component. Circle in lower right corner indicates current amplitude of 50 cm/sec.

Eddies

Several tidal eddies appear in the model, most notably in Admiralty Inlet off the main axis of the tidal flow. An anticlockwise eddy appears during flood tide in Admiralty Bay and similarly in Useless Bay (see Figure 4). The amplitude of the currents associated with these eddies is typically of the order of 40 to 50 cm/sec. These eddies are clearly generated at headlands and captured in coves that lie downstream of them; due to the geometry of the west coast of Whidbey Island, they tend to be pronounced during flood tide.

Another notable feature in the model, striking in the model animation, is a propagating, coastally trapped wave along the western shore of southern Whidbey Island that recurs every tidal cycle. Apparently this wave is generated at the southern end of Whidbey Island at the beginning of ebb tide and propagates into Useless Bay, where it appears to dissipate.

Conclusions

The three-dimensional model of Puget Sound circulation has been successful in reproducing many aspects of the observed tidal circulation of the Sound, while its rich detail is suggestive of further observational verification. The river- and wind-driven components of the circulation also await further investigation and verification with data. We believe the circulation model will become a useful tool in understanding the physical working of the Sound and the circulation's role in the overall marine environment.

Acknowledgments

The author thanks Washington Sea Grant and University Initiative Fund for financial support for the development of the model. Jeff Richey was the motivational force behind PRISM, and Parker MacCready has been a constant source of input and encouragement. Miles Logsdon supplied bathymetric and river discharge data. Mark Stoermer produced excellent model animations that were presented at the Conference. Other graphics in the talk and in this proceeding are produced using the graphics package FERRET from NOAA/PMEL.

References

Blumberg, A.F., and G.L. Mellor. 1987. A description of a three-dimensional coastal ocean circulation model. in Three-Dimensional Coastal Ocean Models, Vol.4, N. Heaps, ed., American Geophysical Union, Washington, D.C. 208 pp.

Cannon, G.A., N.P. Laier, and T.L. Keefer. 1979. Puget Sound circulation: final report for FY77-78. NOAA Tech. Memo. ERL MESA-40. 55 pp.

Flather, R.A. 1976. A tidal model of the northwest European continental shelf. Mem. Soc. R. Sci. Liege, Ser.6, 10: 141-164.

Lavelle, J.W., H.O. Mofjeld, E. Lempriere-Doggett, G.A. Cannon, D.J. Pashinski, E.D. Cokelet, L. Lytle, and S. Gill. 1988. A multiply-connected channel model of tides and tidal currents in Puget Sound, Washington and a comparison with updated observations. NOAA Tech. Memo. ERL PMEL-84. 103 pp.

Mellor, G.L., and T. Yamada.1974. A hierarchy of turbulence closure models for planetary boundary layers. J. Atmos. Sci. 31: 1791-1806.

Mofjeld, H.O., and L.H. Larsen. 1982. Tides and tidal currents of the inland waters of western Washington. NOAA Tech. Memo. ERL PMEL-56. 52 pp.